

HUMAN IN THE LOOP INTEGRATED LIFE SUPPORT SYSTEMS GROUND TESTING

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Human exploration missions beyond low earth orbit will be long duration with abort scenarios of days to months. This necessitates provisioning the crew with all the things they will need to sustain themselves while carrying out mission objectives. Systems engineering and integration is critical to the point where extensive integrated testing of life support systems on the ground is required to identify and mitigate risks. Ground test facilities (human-rated altitude chambers) at the Johnson Space Center are being readied to integrate all the systems for a mission along with a human test crew. The relevant environment will include deep space habitat human accommodations, sealed atmosphere capable of 14.7 to 8 psi total pressure and 21 to 32% oxygen concentration, life support systems (food, air, and water), communications, crew accommodations, medical, EVA, tools, etc. Testing periods will approximate those of the expected missions (such as a near Earth asteroid, Earth-Moon L2 or L1, the moon, Mars). This type of integrated testing is needed for research and technology development as well as later during the mission design, development, test, and evaluation (DDT&E) phases of an approved program. Testing will evolve to be carried out at the mission level – “fly the mission on the ground”. Mission testing will also serve to inform the public and provide the opportunity for active participation by international, industrial and academic partners.

I. INTRODUCTION

Integrated ground testing is relatively benign in terms of both risk and cost – it does not leave the Earth and is easy to access, change, and repeat. Ground-based test facilities and chambers can be used to economically and repeatedly test various operational concepts, technologies, components, and systems in a variety of simulated environments. Ground-based testing allows both individual component and system level testing for certification of advanced technologies and systems before use. “Ground Flight” concepts allow for development of effective management techniques, especially those associated with international and diverse partners. Both simulators and field tests allow “build a little; test a little” to provide greater insight into “go/no go” technical decisions. Test repeatability of hardware performance, development of maintenance procedures, and an understanding of operational support needs are necessary prior to commitment to long-duration missions. In addition, ground-based testing of actual flight hardware in simulated real “flight-like” conditions provides an opportunity to model expected as well as unexpected failure modes while qualifying and certifying hardware for flight. However, it should be noted that it is currently difficult to test complete integrated spacecraft systems for long durations; and, it is difficult to simulate low-gravity / zero-gravity conditions and long duration deep-space environment exposure, including radiation.

II. LIFE SUPPORT SYSTEMS

In broad terms, life support includes air revitalization, water recycling, solid waste handling and processing, and habitation systems including galleys, wardrooms, bathroom facilities, and food provisioning (Figure 1). The goal is to provide an optimum living environment, while reducing the need for resupply of consumables.

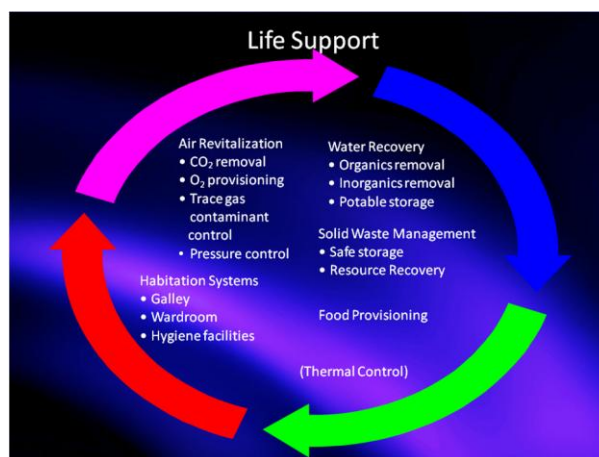


Figure 1: Major functional areas of space based life support

II.I Air Revitalization

Air revitalization includes CO₂ removal, O₂ provisioning, pressure control, air distribution and trace gas contaminant control. Additionally, relative humidity must be maintained at acceptable levels in the crew-occupied areas. Future spacecraft and habitats could operate at total pressures and oxygen concentrations different from those currently in use. A candidate atmosphere is a total pressure of 8 psi and an oxygen concentration of 32%. This was recommended by the Exploration Atmospheres Working Group in 2006.¹ Pressure and oxygen concentration in this range would enhance intensive EVA phases of missions by reducing pre-breathe times and enabling rapid EVAs.

II.II Water Recovery

Water recovery from waste water entails organic and inorganic contaminant removal to spacecraft standards and the sterilization of the water. Potability must be maintained up to the point where the water is consumed by the crew; this is accomplished by using a residual biocide such as silver or iodine. Water is the largest mass item of the life support consumables. Hence very high recovery rates from waste water back to potable water in the range of 95%+ are sought.

II.III Solid Waste Processing

Solid waste processing entails the safe handling of solid wastes and the recovery of resources from solid wastes. These include moisture removal, odor control, sterilization, and safe storage of solid wastes. Recovery of resources from solid wastes is a particular challenge in that the technologies are less mature than for water and air.

II.IV Habitation Systems

The habitation system includes many areas including acoustic control, command & control (including emergency response), crew quarters, exercise provisions, experimentation / work area, food/hydration, galley, hygiene control, lighting, logistics, medical, recreation, and logistics /stowage. The goal is to provide a safe, comfortable, and productive working environment.

Figure 2 shows the simplified inputs and outputs for a crewmember in space. It is crucial to recover useful products from all wastes in order to minimize resupply from Earth. This figure assumes no food production in space; rather, the crew relies on stored food for sustenance. With more mature space systems, plant growth will gradually become the primary source of food for crews.

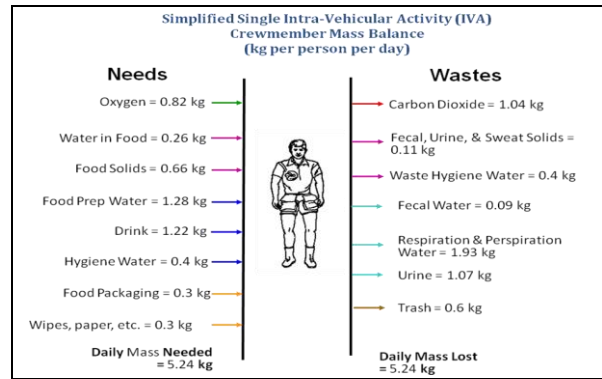


Figure 2: Simplified Single Intra-Vehicular Activity (IVA) Crewmember Mass Balance (kg per person per day)

III. INTEGRATED TESTING

Integrated testing of life support systems is crucial to the success of providing highly reliable, regenerative life support for future long duration exploration missions. Integrated testing allows for the identification of systems risks which then can be mitigated well before flight. Technology development, particularly maturation to higher readiness levels (TRL) (Figure 3), benefits from integrated testing by enabling or informing technology down-select; a necessary step during the maturation process. In order to achieve TRL 6, it is necessary to test "a representative model or prototype system or system, which would go well beyond ad hoc, "patch-cord," or discrete component level bread boarding, would be tested in a relevant environment. At this level, if the only relevant environment is the environment of space, then the model or prototype must be demonstrated in space" (Table 1).² In those cases where the microgravity environment of space is not an important factor, integrated ground testing provides sufficiently robust test conditions to allow a TRL of 6 to be achieved. This test environment also provides the opportunity to test under "off-nominal" conditions to get an assessment of the operating range of technologies.

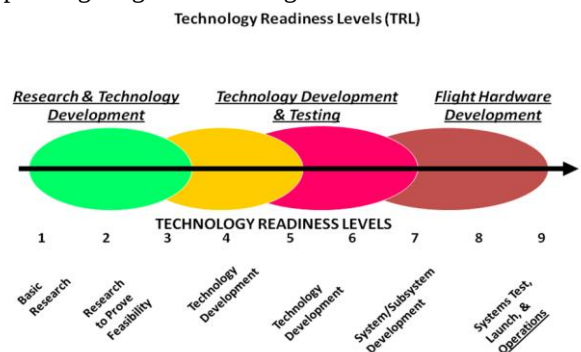


Figure 3: Technology Readiness Levels

Table 1: Technology Readiness Level Definitions²

	Technology Readiness Level	Description
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative, and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2.
4	Component and/or breadboard validation in laboratory environment.	Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the pieces will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier and should also be consistent with the requirements of potential system applications. The validation is relatively "low-fidelity" compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory.
5	Component and/or breadboard validation in relevant environment.	At this level, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, subsystem-level, or system-level) can be tested in a "simulated" or somewhat realistic environment.
6	System/subsystem model or prototype demonstration in an operation environment.	A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system, which would go well beyond ad hoc, "patch-cord," or discrete component level breadboarding, would be tested in a relevant environment. At this level, if the only relevant environment is the environment of space, then the model or prototype must be demonstrated in space.
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system. TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. The prototype should be near or at the scale of the planned operational system, and the demonstration must take place in space. Examples include testing the prototype in a test bed.
8	Actual system competed and "flight qualified" through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this level is the end of true system development for most technology elements. This might include integration of new technology into an existing system.
9	Actual system flight proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. This TRL does not include planned product improvement of ongoing or reusable systems.

Ground testing is relatively benign in terms of both risk and cost – it doesn't leave Earth and is easy to access, change, and repeat. Ground-based test facilities and chambers can be used to economically and repeatedly test various operational concepts, technologies, components, and systems in a variety of configurations and simulated environments. Ground testing with appropriate simulators provides necessary training & experience, both nominal and contingency situations, before committing crew to missions in space. Ground-based testing allows both individual component and system level testing for certification of advanced technologies and systems before use. "Ground Flight" concepts allow for development of effective management techniques, especially those associated with international and diverse partners. Both simulators and field tests allow "build a little; test a little" to provide greater insight to "go/no go" technical decisions. And, ground-based testing of actual flight hardware in simulated real "flight-like" conditions provides opportunity to model expected as well as unexpected failure modes while qualifying and certifying hardware for flight. And finally, if no approved mission is in work, integrated ground testing can also inform mission architectures and concepts of operations through a much better understanding of the technology and the systems needed for the eventual mission.

IV. PAST INTEGRATED TESTING

Have we ever done this type of high-fidelity ground testing of highly integrated life support systems? The answer is yes. In 1996 and 1997 three major integrated tests were carried out in a large chamber at the Johnson Space Center (Figure 4). This chamber, called the 20-foot chamber, was used to test various combinations of advanced life support systems technologies. Four person crews were continuously sequestered in the atmospherically sealed chamber for 30 days, 60 days, with the last test in the series lasting 91 days.^{3,4} Each of the three tests were successfully completed without interruption and all life support technologies were evaluated. The 91-day test utilized biological systems for the primary means of water recovery and employed a combination of mechanical and biological systems to revitalize the air. A module containing a wheat crop was linked to the test chamber to provide up to 25 percent of the crew's oxygen from the carbon dioxide produced by the crew in the 20-foot chamber. Water consumed by the crew was recycled using a unique biological and physicochemical water recovery system. Solid waste from the crew was incinerated to produce additional carbon dioxide to sustain plant growth for air revitalization and food production.

During these tests, additional information was gained that would likely have not been uncovered until much later. One important finding had to do with trace gas contaminants in the atmosphere where, with the exception of formaldehyde, all trace gas contaminants were kept within acceptable Spacecraft Maximum Allowable Concentrations (SMAC). However, the formaldehyde level was approximately 0.16 ppm throughout the test. The 7-day SMAC is 0.04 ppm, and the threshold limit value for industrial workers is 0.30 ppm. The primary source of formaldehyde was later identified to be the acoustic tile used throughout the chamber walls and ceilings, while the carpeting was identified as a secondary source. Subsequent to this test, formaldehyde was added to the list of gas species for which all space flight equipment had to be tested.

Another outcome of these tests involved iodine. Iodine was used as a residual biocide in the potable water tanks to insure the water remained potable until used by the crew. Consumption of the additional iodine during the test resulted in thyroid irregularities. The test protocol was changed to remove the iodine as a precaution prior to human consumption. The Shuttle flight program also implemented an iodine removal capability on subsequent flights. These two examples illustrate knowledge gained through ground testing that can help insure flight crews can carry out their mission objectives safely.



Figure 4: The 20-foot chamber at the Johnson Space Center used for a series of integrated life support testing in 1996 and 1997^{3,4}

V.FUTURE INTEGRATED TESTING

As we prepare for future human exploration missions to destinations such as a Near Earth Asteroid (NEA), Cis-lunar locations, the moon, the moons of Mars and Mars, it is the research and technology development which will provide the new technologies to make such missions feasible. Inherent in technology development is the absolute necessity to mature it to levels where a flight program can adopt or baseline that technology to take it to flight. Implicit in that is the need for integrated testing of technologies into a system to fully verify and mature the technology. Figure 5 illustrates the relationship between destination in terms of distance from Earth and the needed technology maturity in terms of life support “closure”. The basis for all destinations is a robust technology development activity including ground based integrated testing. Our flight experience to date is certainly our point-of-departure for technologies, but requirements for destinations far from Earth dictate that improved life support technologies are needed in terms of reliability and closure.

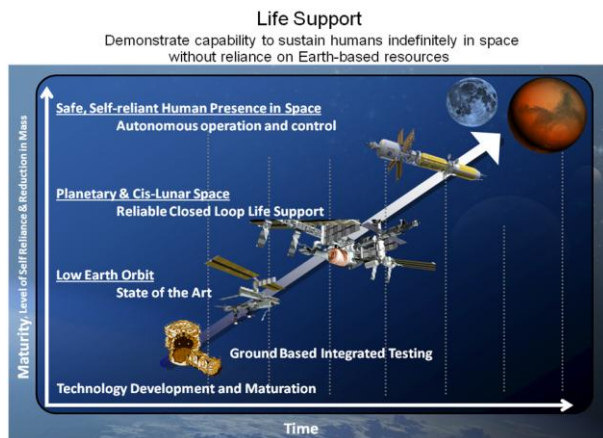


Figure 5: Relationship between distance from Earth and life support “closure”

To fulfill the need for integrated testing of life support systems as well as other systems for human exploration missions, the Johnson Space Center is preparing a test facility capable of conducting long duration, human-in-the-loop testing. The 20-Foot Chamber (Figure 4) has been used in past testing with human test crews and will again accommodate similar testing.

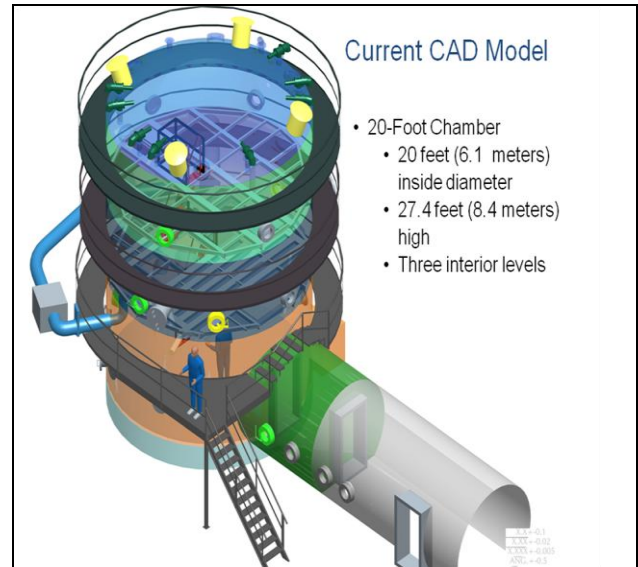


Figure 6: ProE CAD model of the 20-foot chamber



Figure 7: Interior of the 20-foot chamber; A is level 3, B is level 1, and C is the man lock

A ProE⁵ model of the chamber is being prepared to aid in test buildup (Figure 6). The chamber is 20 feet in diameter and 27.4 feet high with three interior levels (Figure 7). Figure 7 contains photos of the first and third levels and the man lock. The chamber is ready for interior design as a habitat and is capable of tight seal and a range of atmospheric pressures and oxygen concentrations to match test designs. Figure 8 is the CAD model of the man lock and outer man lock of the 20-foot chamber. These transfer locks are the primary access to the chamber used during test buildup and preparation. They are also used to change crews and large equipment during tests while minimizing impacts to the test by controlling

atmospheric gas losses and mixing with outside gases. In addition, a small transfer lock within the main chamber allows the exchange of small items (e.g., food, water, medicines) on a routine basis. The red box depicted in Figure 8 is illustrative of the maximum size equipment which will fit through the hatches and can be moved into the first level of the three-level chamber. Figures 9 and 10 are the CAD models of the second and third levels of the chamber showing boxes representing the dimensions of equipment which can be passed from the first to the second level and from the second to the third level via the existing pass throughs.

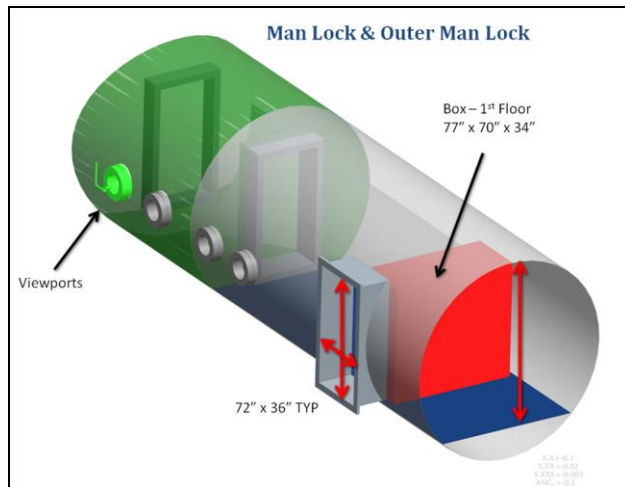


Figure 8: CAD model of the 20-foot chamber man lock and outer man lock for accessing the chamber. The red box is illustrative of the maximum sized equipment that will pass through the hatch and which can be moved to the first level of the chamber.

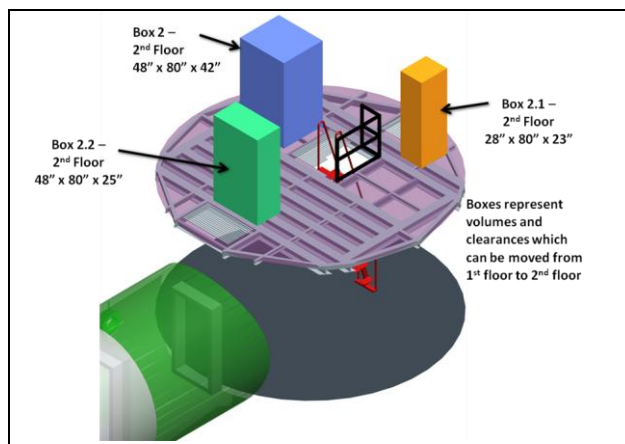


Figure 9: CAD model of the 20-foot chamber depicting the second level and boxes illustrating the size of equipment which can be moved from the first to the second level.

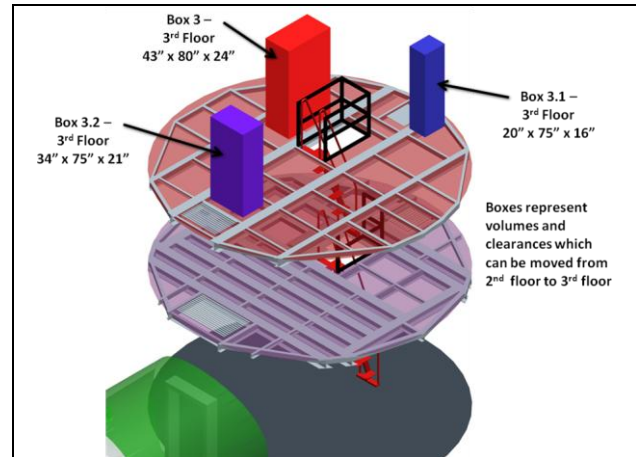


Figure 10: CAD model of the 20-foot chamber depicting the third level and boxes illustrating the size of equipment which can be moved from the second to the third level

VI.CONCLUSION

Integrated ground testing is crucial to future human exploration missions beyond low Earth orbit (LEO) both in terms of developing and maturing technologies needed as well as during design and development of the flight hardware after a mission is approved. The Johnson Space Center is preparing to carry out extensive long duration ground tests to integrate complete life support systems with human test crews to thoroughly verify the efficacy of technologies for the future.

Future human mission beyond LEO will be international undertakings. Partnering is the best way to leverage technologies and resources to enable future missions to be accomplished. Integrated ground testing even before a specific mission is approved can serve to not only mature and validate needed technologies but can serve to gain experience with partners in this great venture into space.

VII. REFERENCES

1. NASA Exploration Atmospheres Working Group. Recommendations for exploration spacecraft internal atmospheres: The final report of the NASA exploration atmospheres working group. NASA Technical Publication NASA/TP-2010-216134, Johnson Space Center, Houston, TX, October 2010, 178 p.
2. NASA Procedural Requirements (NPR) 7123.1A, NASA Systems Engineering Processes and Requirements, NASA Interim Directive (NID) NASA Systems Engineering Processes and Requirements, NID 7123-69, 2009, p 128.
3. Isolation - NASA Experiments in Closed-Environment Living - Advanced Human Life Support Enclosed System, edited by Helen W. Lane, Richard L. Sauer, and Daniel L. Feedback, Volume 104, Science and Technology Series, A Supplement to Advances in the Astronautical Sciences, American Astronautical Society, San Diego, California, 451 p.
4. Lunar-Mars Life Support Test Project: Phase III Final Report, CTSD-ADV-341, Engineering Directorate, Crew and Thermal Systems Division, Houston, TX, February 23, 2000.
5. ProE, Pro/Engineer Wildfire 4.0, Software Package, Ver. 4.0, Parametric Technology Corporation (PTC), Needham, MA, 2008.